Tracking Endocardium Using Optical Flow along Iso-Value Curve

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Outline

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- Method
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- Conclusion

Introduction

- Cardiac imaging modalities (US, MRI,CT, SPECT/PET) provide structural and functional information.
- **Quantitative** evaluation of cardiac function usually requires endocardial border **segmentation** throughout the whole cardiac cycle.
- With recent advancements in high temporal and spatial resolution imaging, manual analyses become prohibitively labor-intensive.

Introduction

- Cardiac image segmentation: active contour, level set, classification, active appearance model, etc.
- Cardiac motion tracking: optical flow techniques
- Cardiac displacements along specific directions may be better indicators.
- A framework of optical flow along iso-value curves is proposed and applied to several cardiac applications.

Optical Flow (OF)

- Refers to the computation of the displacement field of objects in an image.
- Assumes intensity of the objects remains constant.
- First proposed in 1980s and drove the active area of motion analysis in 1990s.

Optical Flow

- Optical flow constraint equation:
  - Intensity constancy assumption for image *I*:

$$I(x+dx, y+dy, t+dt) = I(x, y, t)$$

  - Using Taylor series expansion and take limit of $dt \to 0$:

$$\boxed{I_x u + I_y v + I_t = 0}$$

Optical flow constraint equation

where:

$$u = \frac{dx}{dt}, v = \frac{dy}{dt}$$

$$I_x = \frac{\partial I}{\partial x}, I_y = \frac{\partial I}{\partial y}, I_t = \frac{\partial I}{\partial t}$$

Optical Flow

- The optical flow problem cannot be uniquely solved by the *OF constraint equation* (under-constrained). $I_x u + I_y v + I_t = 0$
- All gradient-based OF methods try to add additional constraints to make the system sufficiently or even over-constrained.
- E.g. the Lucas-Kanade (LK) method tries to solve the equation through a weighted least-squares fitting in each small neighborhood Ω.

LK Method

- LK method is equivalent to minimizing the following energy:

$$\sum_{(x,y)\in\Omega} W^2(x,y)\left[I_x u + I_y v + I_t\right]^2$$

which can be solved via the following linear system:

$$A^T W^2 A \begin{bmatrix} u \\ v \end{bmatrix} = A^T W^2 \mathbf{b}$$

$$A = \begin{bmatrix} I_{x_1} & \cdots & I_{x_n} \\ I_{y_1} & \cdots & I_{y_n} \end{bmatrix}^T, W = diag\left[W(x_1, y_1), \quad \cdots, \quad W(x_n, y_n)\right], \mathbf{b} = -\begin{bmatrix} I_t(x_1, y_1) \\ \vdots \\ I_t(x_n, y_n) \end{bmatrix}$$

OF along Iso-value Curves

- In myocardial motion analysis, motion fields are projected along specific direction:
  - E.g. thickening (radial derivative of radial displacement) is the best indication for ischemia
- With proper selection of coordinate systems, displacement along some direction can be formulated as motion along some iso-value curves.

OF along Iso-value Curves

- This can be formulated as adding additional constraint of the *OF constraint equation* with *f=0* as the iso-value curves:

$$\begin{cases} I_x u + I_y v + I_t = 0 \\ f(x, y, u, v) = 0 \end{cases}$$

- Analog to LK method, the final optical flow can be solved via energy minimization of

$$\sum_{(x,y)\in\Omega} W^2(x,y)\left[I_x u + I_y v + I_t\right]^2 + f^2(x_c, y_c, u, v)$$

- Solving this system is non-trivial depending upon the linearity of *f*.

Application 1

- A direct application is to track endocardium along radial direction in 2D.
- The problem can be formulated as OF along $\theta = const$ in polar coordinates.
- The constraint can be derived as:

$$f(x_c, y_c, u, v) = y_c u - x_c v = 0$$

- The energy minimization can be solved by least-square fitting of following over-constrained system:

$$\begin{bmatrix} \sum W^2 I_x^2 & \sum W^2 I_x I_y \\ \sum W^2 I_x I_y & \sum W^2 I_y^2 \\ \hline y_c & -x_c \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} A^T W^2 \mathbf{b} \\ \hline 0 \end{bmatrix}$$

Evaluation

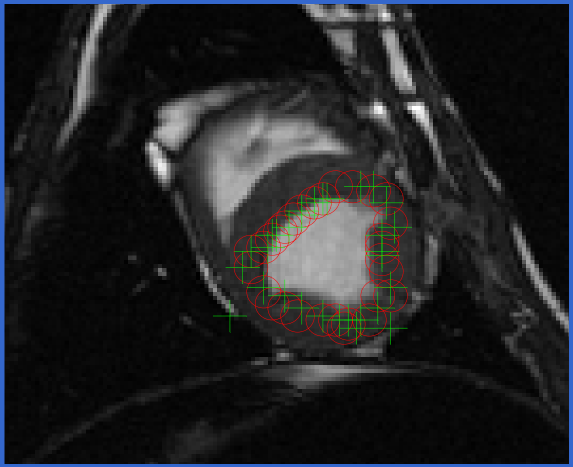
- Data: 2D cardiac MRI series with ECG gating acquired by GE 1.5T (FIESTA)
- Subject: LAD occlusion in sheep hearts.
- Endocardial border points for each time frame were traced by an experienced expert.
- Optical flow algorithm initialized with manual tracing points on the first frame (end-diastole) and ran to track surface points throughout the whole cardiac cycle (20 frames in total).

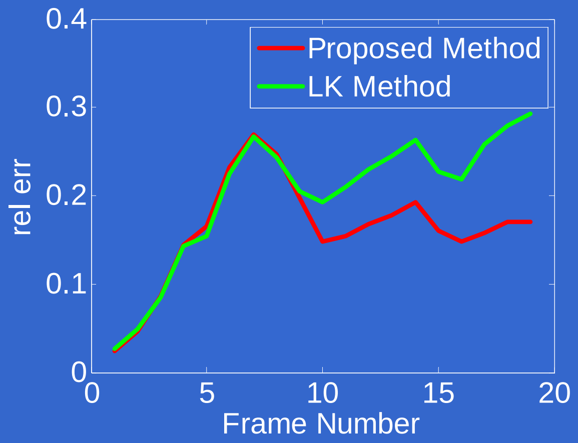
Evaluation

- Two error measurements were used
  - Tanimoto index (TI)
  - Relative errors in radial coordinates.
- A 24 FEM is fitted to endocardial surfaces
- The relative errors in radial coordinates of each element were then computed, with its mean served as a performance indicator for each frame.

Results

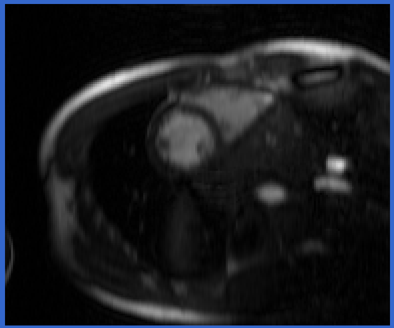
- Tanimoto Index:
  - Our method: 74.62%±8.54%
  - Lucas-Kanade: 72.06%±9.13%
- In terms of relative error, our method is less likely to fail in later frames.





Application 2

- 2D Endocardium tracking in high-temporal resolution MR images*:
  - With 2ms temporal resolution on average
  - About 400 frames per cardiac cycle

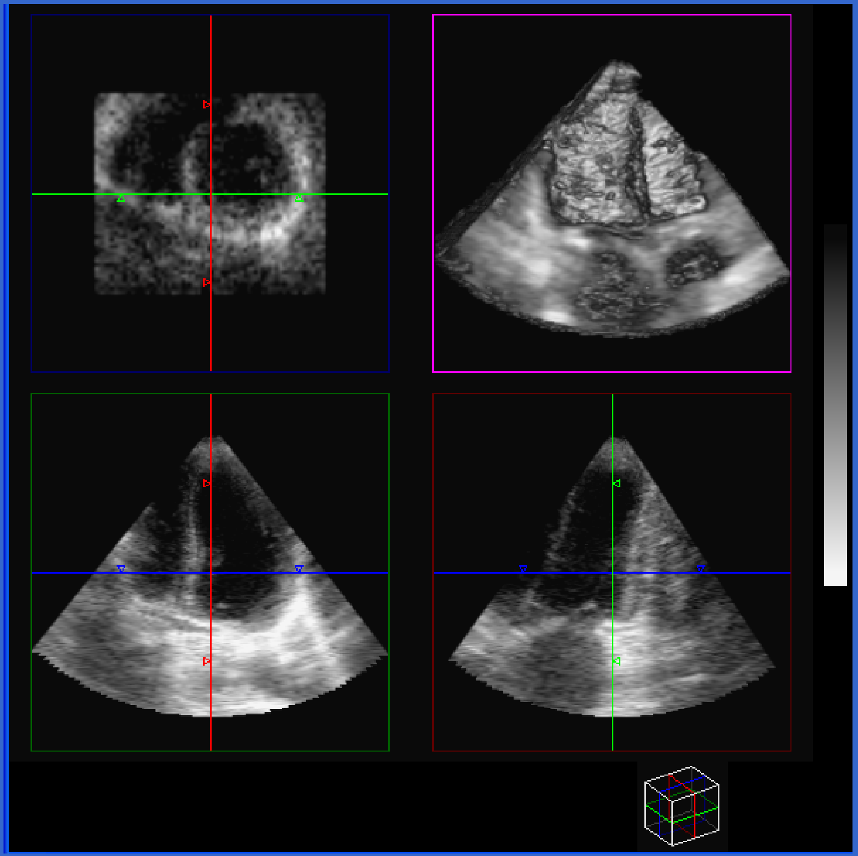


- Relative tracking error after 130 frames:
  - Our method: 7.10%±9.53%
  - Lucas Kanade method: 13.34%±28.59%

*V. Pai, L. Axel, and P. Kellman, "Phase Train Approach for very high temporal resolution cardiac imaging," J Cardiovasc Magn Reson, vol. 7, pp. 98-99, 2005.

Application 3

- 3D Endocardium tracking in real-time ultrasound images:
  - Proposed method was extended in 3D.
  - Correlation based optical flow was implemented both freely in 3D and along radial direction.
  - FEM based surface comparison method* was used.

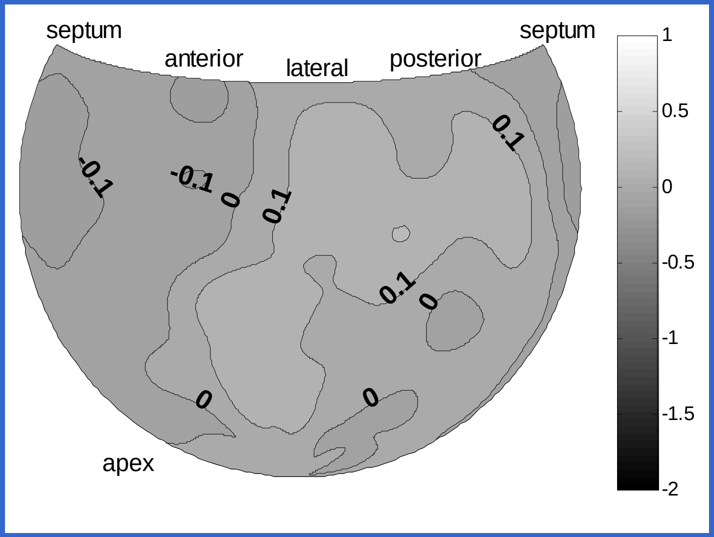


*Q. Duan, E. D. Angelini, S. L. Herz, O. Gerard, P. Allain, C. M. Ingrassia, K. D. Costa, J. W. Holmes, S. Homma, and A. F. Laine, "Tracking of LV Endocardial Surface on Real-Time Three-Dimensional Ultrasound with Optical Flow," presented at Third International Conference on Functional Imaging and Modeling of the Heart 2005, Barcelona, Spain, vol. LNCS 3504, pp. 434-445, 2005.

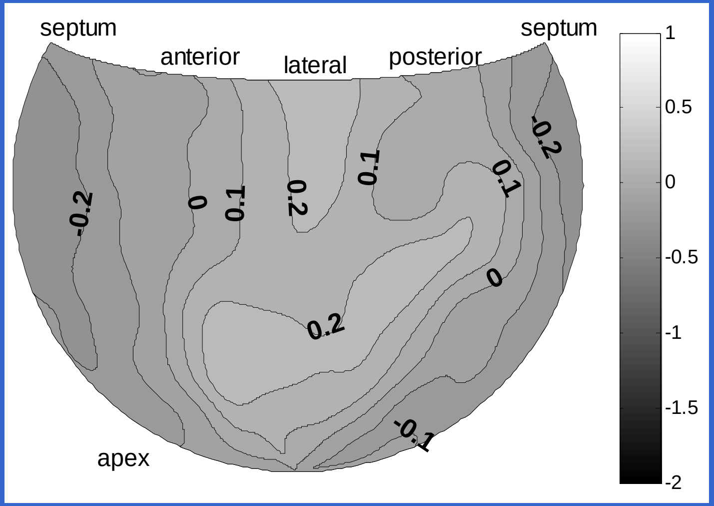
Application 3

- Quantitative surface comparison:
  - Constrained: 68.92% under 10% difference
  - Direct method: 38.37% under 10% difference

Constrained

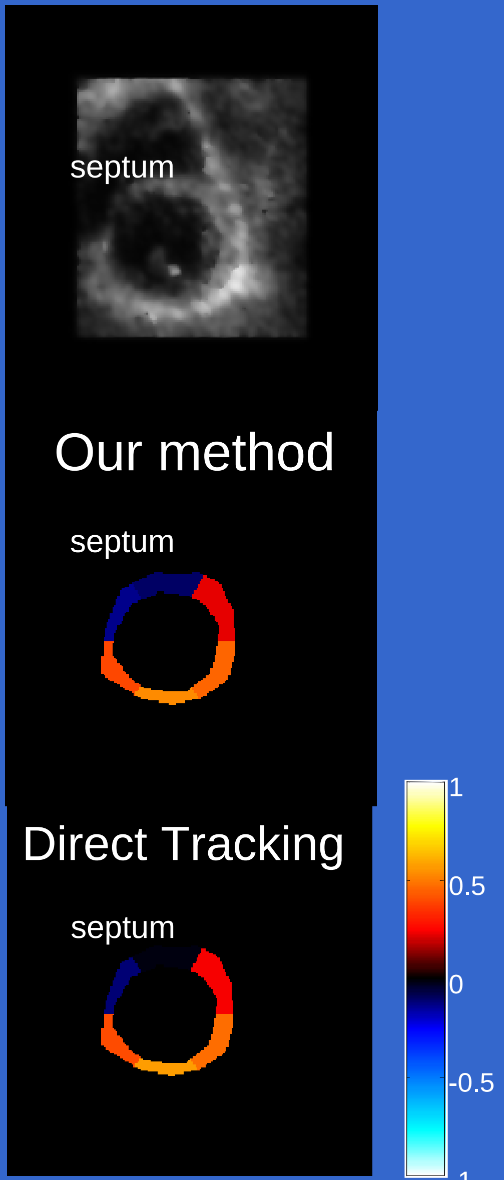


Direct method



Application 4

- Thickening computation on 2D slice from 3D real-time ultrasound
  - Patient after heart transplant
  - Segmental average thickening maps were computed based on radial displacement estimated from optical flow tracking.
  - Despite the slight difference in the value, both methods correctly indicated the reduced motion at the septum.



Conclusions

- A generic framework for optical flow along iso-value curves was proposed as an energy minimization problem with local constraints related to iso-value curves.
- Applications of this framework were presented for tracking of the endocardium on 2D MRI data series and 3D real-time ultrasound volumes.
- The endocardium borders tracked by the proposed method as well as the Lucas-Kanade method were quantitatively compared to manual tracing.
- The results showed superior performance for the proposed method in tracking the endocardium.
- The framework is generic and can be readily extended to n-dimensional spaces with little effort to properly define the iso-value curves and solve as a non-linear energy minimization problem.

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Thank you!

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